Coronal Temperature as an Age Indicator

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ABSTRACT

The X-ray spectra of late type stars can generally be well fitted by a two temperature component model of the corona. We find that the temperatures of both components are strong functions of stellar age, although the temperature of the hotter plasma in the corona shows a larger scatter and is probably affected by the activity of stars, such as flares. We confirm the power-law decay of the temperature of the hot plasma, but the temperature of the cool plasma component decays linearly with log(age).

Key words : stars: coronae – X-ray: stars – stars: age

I. Introduction

Since the launch of *ROSAT*, the X-ray properties of late type stars, especially late type stars in open clusters, have been extensively studied and are now well understood in terms of a stellar activity - rotation - age paradigm. In most cases the investigators have derived the X-ray luminosities and X-ray to bolometric luminosity ratios of stars, the X-ray luminosity function of clusters, and compared them with other clusters (see Franciosini et al. (2003) for example). Owing to the better light collecting power and high angular resolution of the *Chandra* X-ray Observatory and XMM-*Newton*, it is now possible to identify the X-ray sources unambiguously and to determine the temperature of stellar coronae.

Previously it was thought that the coronal temperature depended on the spectral-type of stars (Jordan & Montesinos 1991) and showed a clear difference between that of F type stars and that of G/K type stars. But the coronal temperatures of G and K type stars during quiescence are very similar (see Fig. 1, see also Fig. 5 of Pillitteri et al. 2006).

Schmitt et al. (1990) published an extensive analysis of the X-ray properties of late-type stars based on data obtained with the *Einstein* Observatory. They showed that models employing continuous emission measure distributions provide equally adequate and physically meaningful and more plausible descriptions of the phenomena. Recently Marino et al. (2005) showed that the X-ray spectra of the G, K and M type stars in IC 2391 are well described by two thermal components, although the instrument was capable of identifying up to 3 thermal components.
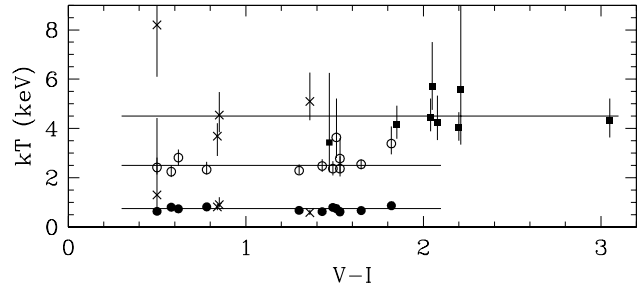

Fig. 1.— Coronal temperatures of late type stars in NGC 6231 (Sana et al.2007). Filled and open circles represent, respectively, the lower and higher temperatures from two-temperature model fits of spectra unaffected by flaring events, while crosses denote those affected by the flare. The squares are the temperatures of flares from a single temperature model fit.

In this paper, we compile the coronal temperature of G and K (up to M, if possible) type stars in open clusters for cases where the quality of the data was good enough to fit the X-ray spectra with a two temperature model and where, if possible, the X-ray spectra was not affected by a flaring event. In this paper we highlight the possibility that coronal temperature is an age indicator. In §2 and §3, we describe the data selection and derive the relation between the average X-ray temperature and the age of open clusters. A possible reason for the existence of such a relationship is speculated in §4.

II. Data

Getman et al. (2005) published results from extensive observations of the Orion nebular cluster with the

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TABLE 1. Average coronal temperatures of open clusters and stars

Cluster	Age (Myr)	Observatory	$< kT_1 >$	$< kT_2 >$	N	source and criteria for data selection
Orion	$<1.0^{(1)}$	CXO	0.798 ±0.156	2.897 ±1.520	209	Getman et al. (2005) : Sp ≥ G, $\chi^2 \leq 1.50$, d.o.f ≥ 21, no flare
NGC 2264	$3.1^{(2)}$	CXO	0.87 ±0.13	2.32 ±0.86	8	Flaccomio et al. (2006) : F_X ≥ -13.0
NGC 6231	$5.0^{(3)}$	XMM-Newton	0.72 ±0.09	2.87 ±0.53	12	Sana et al. (2007) : $V - I \geq 0.5$ no flare
GJ 3305	$13^{(4)}$	CXO	0.6	2.8	1	Feigelson et al. (2006)
NGC 2547	$30^{(5)}$	XMM-Newton	0.61 ±0.03	1.45 ±0.21	4	Jeffries et al. (2006)
IC 2391	$53^{(6)}$	XMM-Newton	0.40 ±0.09	1.10 ±0.11	4	Marino et al. (2005)
Pleiades	$115^{(7)}$	XMM-Newton	0.44 ±0.12	1.07 ±0.14	11	Briggs & Pye (2003)
NGC 2516	$160^{(8)}$	XMM-Newton	0.52 ±0.18	1.67 ±0.74	15	Pillitteri et al. (2006) : d.o.f. ≥ 20
Praesepe	$650^{(9)}$	XMM-Newton	0.40 ±0.01	0.90 ±0.01	2	Franciosini et al. (2003)
Sun	$4,600^{(10)}$	ASCA (simulated)	0.216 ±0.002	0.565 ±0.019	-	Peres et al. (2000) : for solar maximum

Source of age – $^{(1)}$: Hillenbrand (1997), $^{(2)}$: Sung, Bessell, & Chun (2004), $^{(3)}$: Sung et al. (2008, in preparation), $^{(4)}$: Feigelson et al. (2006), $^{(5)}$: Jeffries et al. (2006), $^{(6)}$: Barrado y Navascués et al. (1999), $^{(7)}$: Basri, Marcy, & Graham (1996), $^{(8)}$: Sung et al. (2002), $^{(9)}$: Franciosini et al. (2003), $^{(10)}$: Barnes (2007)

Chandra X-ray Observatory. In their Tables 6 and 9, they presented the X-ray properties of late-type stars in their quiescent state. We averaged the coronal temperatures of 209 stars of spectral-types later than G, whose spectra could be fitted with two thermal components, and whose reduced chi square (χ^2) was less than 1.5 and degree of freedom was larger than 21. As in Fig. 11 of Preibisch et al. (2005), the lower temperature component shows no dependence on the stellar photospheric temperature, although the higher temperature component does show a weak dependence on photospheric temperature. In the current analysis we disregarded the weak dependency on photospheric temperature because we could find no such dependency in data from other open clusters or stars.

For NGC 2264, we selected the X-ray temperatures of 8 stars whose observed X-ray flux ($\log F_X \geq -13.0$) from Flaccomio et al. (2006). If we lessen this criterion to $\log F_X \leq -13.5$ (but still exclude the data whose higher temperature is an upper limit or the error is an upper limit), the average temperatures are slightly lower and so provide a better fit to the relation in Fig. 2.

For NGC 6231, we selected the XMM-*Newton* data from Sana et al. (2007). As shown in Fig. 1, we took an average for the stars whose spectra were not affected by a flaring event. For the nearby young star GJ 3305, Feigelson et al. (2006) presented the coronal tempera-

ture without providing the errors.

For the Pleiades, Daniel et al. (2002) presented the results from the *Chandra* X-ray Observatory, but they assumed the temperature of the higher temperature component was $kT_2 = 3.5$. We only took the Briggs & Pye (2003) XMM-*Newton* data. Pillitteri et al. (2006) presented extensive observations of NGC 2516 with XMM-*Newton*. We took the average temperature of X-ray sources whose degree of freedom of spectral fit was greater than 20.

Franciosini et al. (2003) presented results from the spectral analysis of three bright stars in Praesepe based on data obtained with XMM-*Newton* observation. Two stars met our selection criteria. Stern et al. (1994) published the coronal temperature of the stars in the Hyades. As the data were obtained with *ROSAT*/ PSPC, the temperatures are systematically lower and so the data were not taken into account.

Peres et al. (2000) simulated the synthetic *ROSAT*/ PSPC and *ASCA*/SIS spectra of the sun and presented the resulting temperatures. As *ROSAT*/ PSPC gives systematically lower temperatures and *ASCA*/SIS has similar spectral response to *Chandra* or XMM-*Newton*, we took the simulated temperature from *ASCA*/SIS for the solar maximum.
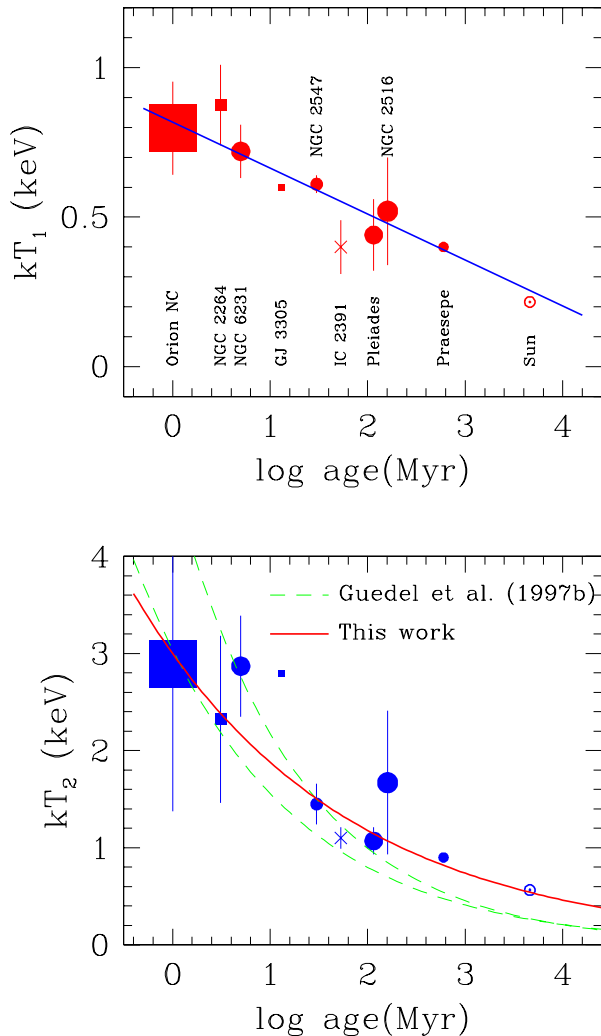
Fig. 2.— Coronal temperatures of stars and the ages of open clusters. (a) lower temperature versus age relation. (b) higher temperature versus age relation. Squares and dots represent respectively the data obtained with the *Chandra* X-ray Observatory and XMM-*Newton*, while the coronal temperature of the sun is from simulated ASCA data for the solar maximum. The cross represents the data for IC 2391 which were excluded in the regression. The size of a symbol is proportional to the number of stars used in calculating the average temperature. The solid and dashed lines represent respectively the relations from this study and those from Güdel et al. (1997b).

III.   Coronal Temperature and Stellar Age

Using the data compiled from the literature, we drew the relation between age and coronal temperature shown in Fig. 2. The relation between the average temperature of the lower temperature component and the age of the cluster is quite good. Only the stars in IC 2391 show a large deviation.

We fitted the following linear regressions to the data (excluding the data for IC 2391). In the regression we applied weights to the data points. The weights applied were proportional to the square root of the number of stars used in the average.

$$kT_1 = 0.818(\pm 0.025) - 0.154(\pm 0.018) \cdot \log \tau (\mathrm{Myr}) \quad (1)$$

$$\log(kT_2) = 0.477(\pm 0.032) - 0.203(\pm 0.025) \cdot \log \tau (\mathrm{Myr}) \quad (2)$$

Güdel et al. (1997b) derived a similar relation for the hotter component using the *ROSAT* data for solar-type stars. But the power they obtained was -0.34 (for a Raymond-Smith model) or -0.29 (for a MEKAL model) (see the dashed lines in Fig. 2), rather than -0.203 ($\pm$ 0.025) in equation (2). They used the data for older stars (the youngest star among them is EK Dra, a Pleiades moving group member- about 100 Myr). In addition the temperature from *ROSAT* is rather lower than that determined using the data obtained with *Chandra* or XMM-*Newton*. As can be seen in Fig. 2, the slopes for τ (age) $\geq$ 100 Myr are very similar.

The value of both the low and high temperature components and the age of open clusters are seen to be well correlated, but the relation for the higher temperature component shows a somewhat larger scatter. As can be seen in Fig. 1, the lower temperature component is nearly independent of flaring events. Although the X-ray spectra are affected by the flaring events, the temperature of the cool component of the plasma is very similar to that of the other stars whose spectra are not affected by a flaring event. On the other hand, the temperature of the hot component is strongly affected by the flare (see for the case of YY Gem : Güdel et al. (2001b) or AB Dor : Güdel et al. (2001a)).

Among the clusters and stars in Table 1, NGC 6231, 2516, and a binary system GJ 3305 have higher values of kT_2. Sung et al. (2002) suggested that the high X-ray activity among the stars in NGC 2516 may be related to the high binary frequency of the cluster. Close binary systems such as RS CVn type binaries show strong, long-lasting X-ray activity owing to the tidal forces they exert on each other. The large scatter in the temperature of the hot plasma could therefore be interpreted either as resulting from flaring activity or from the binarity.

IV.   Discussion

(a)   IC 2391

The data for IC 2391 show a large deviation from the regression line and is neglected in the regression in §3. The four X-ray emission stars in IC 2391 are slightly brighter at a given $(B - V)$ or $(V - I)$. Their location in the color-magnitude diagram is also strongly affected by contamination due to background stars in the Perseus arm (see Fig. 2 of Patten & Pavlovsky (1999) or Fig. 2 of Rolleston & Byrne 1997). In addition, the X-ray temperature of these late type stars is lower than that of the early type stars (VXR 46 & 56 in IC 2391) whose X-ray emission is due to the coronal emission from late type companions. In the Pleiades, two early type stars (HII 1234 & 1384 - Briggs & Pye 2003) show similar temperatures (kT_1 & kT_2) to those of late type stars.

It is interesting that the coronal temperature of VXR 37 is very low even though the spectrum was affected by a flare. As seen in Fig. 1, the temperature of flares of stars in NGC 6231 is much higher, and even the temperature of a solar-like flare is between $kT = 1.2 - 4.4$ keV (Kobayashi et al. 2003; Peres et al. 2000). We suggest that either these stars are not members of IC 2391 or their temperatures have been determined incorrectly.

(b)   Possible Interpretation

Güdel et al. (1997a) analyzed the X-ray and extreme ultraviolet spectra of the young solar analog EK Draconis and found that the distribution of the differential emission measure was essentially bimodal. The two peaks they found was interpreted as simply reflecting the variation with energy of the radiative cooling function of a thermal, optically thin plasma. The emission measure distribution of AB Dor (Sanz-Forcada, Maggio & Micela 2003) also shows two prominent peaks at $\log T_e = 6.9$ and 7.3. In fact, Gehrels & Williams (1993) suggested that the bimodal distribution of coronal temperature of late type stars could be caused by the two local positive slopes in the cooling curve of an optically thin plasma. But our data shown in Fig. 2 do not show any clustering near 0.6 keV or near 0.1 keV. The change in the average coronal temperature is rather a monotonic function of cluster age. And therefore the phenomena we found cannot be interpreted as resulting from the radiative cooling curve of a thin plasma.

Barnes (2003a) extensively studied the rotational evolution of solar- and late-type stars and identified the existence of two sequences in the rotational period vesus color plane. He confirmed the "so-called" Skumanich style spin-down process for late-type stars having a dominant Sun-like, *interface* magnetic field. In addition he identified a *convective* sequence of fast rotators in open clusters that possessed only a convective field, which was not only unable to deplete angular momentum but also incapable of coupling the surface convection zone to the inner radiative zone. Barnes (2003b) attempted to interpret the relation between X-ray emission and rotation in terms of his classification of rotating stars.

Güdel et al. (1997b) successfully reproduced the hot temperature tail of the coronal differential emission measure using the time evolution of the physical properties of solar flares. From Fig. 1, we could also surmise that the hot plasma component is associated with flaring events. But the flares involved with the hot temperature plasma may comprise many successive microflares that cannot be resolved with point-source observations.

On the other hand, the decline in the temperature of the cool component cannot be explained by the usual flaring events. Parker (1988) suggested nanoflares as a possible heating source for the solar X-ray corona. Another proposed mechanism of heating the solar corona is heating by Alfvén waves due to the inhomogeneity of the magnetic field (Heyvaerts & Priest 1983). Although this mechanism cannot explain the occurrence of flares, it could heat a relatively wide region. As can be seen in Fig. 2, although both processes have a dependency on the strength of the magnetic field and consequently could explain the time evolution of coronal temperature, the physical process involved in the heating of the cool plasma could differ from that of the hot plasma.

Very recently De Pontieu et al. (2007) found (at least) two types of spicules in the solar limb from the time-series Ca II H filter observation with the Solar Optical Telescope on board the Japanese solar mission *Hinode*. While type-I spicules are less dynamic and show in many cases a parabolic motion, type-II spicules are very dynamic, have a shorter lifetime and show apparently fast upward speeds between 40 $km\ s^{-1}$ and 300 $km\ s^{-1}$. Many spicules of both types undergo significant transverse motions which can be interpreted as Alfvénic motions. They suggested that the Alfvén waves carry an energy flux and play a significant role in the heating of the corona of the quiet Sun and in accelerating the solar wind. Although we have no definite grounds for rejecting nanoflares as a possible heating source of the cool component, we favour Alfvén waves as the source of heating of the cool plasma component of the stellar coronae.

V.   Conclusions

From this study, we find that

(1) The temperature of the cool component of the coronal plasma is less affected by stellar activity and is a better indicator of stellar age. The coronal temperature of the cool component decreases linearly with the $\log(age)$ of a star/cluster.

(2) The temperature of the hot component can also be used as an indicator of stellar age, but is affected by stellar activity, such as flares.

(3) The X-ray temperature of the hot plasma decreases with about the -0.2 power of stellar age. This slope from our data is greater than that obtained by Güdel et al. (1997b) (about -0.3).

(4) The difference in the age-dependency of the coronal temperature of the hot and cool plasmas could indicate differences in the heating mechanisms of the two components. We favour Alfvén waves as the source of heating of the cool plasma.

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